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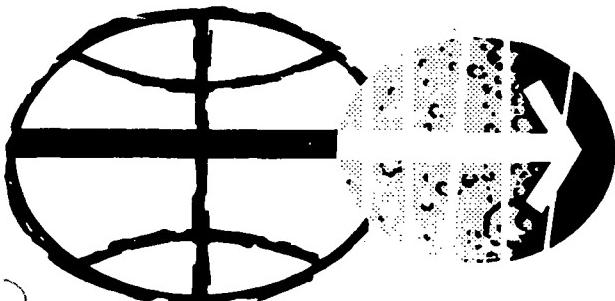
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ANOMALY REPORT NO. 2

WATER/GLYCOL TEMPERATURE CONTROL
CIRCUIT FAILED IN THE AUTOMATIC MODE



MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
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APOLLO 16 MISSION

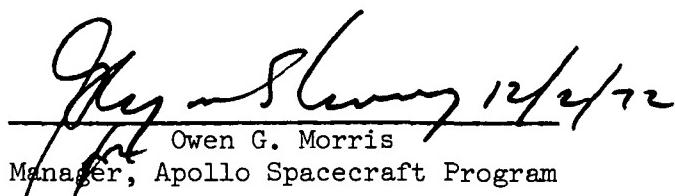
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WATER/GLYCOL TEMPERATURE CONTROL
CIRCUIT FAILED IN THE AUTOMATIC MODE

STATEMENT OF ANOMALY

The water/glycol temperature control circuit (fig. 1) malfunctioned in the automatic mode about 3 hours into the mission. The malfunction allowed an excessive amount of hot water/glycol to bypass the radiator, causing the temperature of the mixed water/glycol to exceed the upper control limit of 48° F. After remaining in the maximum bypass flow position for 5 minutes, the temperature control valve cycled regularly between the maximum bypass flow and minimum bypass flow condition for about 14 minutes before again stopping at maximum bypass flow. The control was changed to the manual position and back to the automatic position to restart the valve operation. This was not successful in restoring normal operation and the valve was placed in the manual position at the desired temperature valve setting. Variations in the evaporator outlet temperature and total system flow rate for the 14-minute erratic period are shown in figure 2. Control valve operation is evident from the variation in system flow rate.

The temperature control valve was positioned manually several times during the mission to maintain the coolant loop temperatures at acceptable levels. During an attempt to return the valve to automatic operation before the transearth extravehicular activity, the valve operated correctly for a short period of time.

SYSTEM DESCRIPTION

The spacecraft cabin atmosphere and electrical equipment temperatures are maintained at desired levels by the water/glycol coolant loop. Heat is rejected by the coolant as it circulates through the space radiators and the water evaporator (fig. 1). An automatic valve controls the coolant bypass flow around the radiators to maintain the desired evaporator inlet temperature of $45 \pm 3^{\circ}$ F.

The temperature controller (fig. 3) uses a thermistor to sense the coolant temperature. The thermistor operates in a resistance bridge that is in balance when the thermistor is at 45° F. The bridge output drives two amplifiers operating as a differential amplifier. When the sensed temperature decreases below 45° F, the thermistor resistance increases

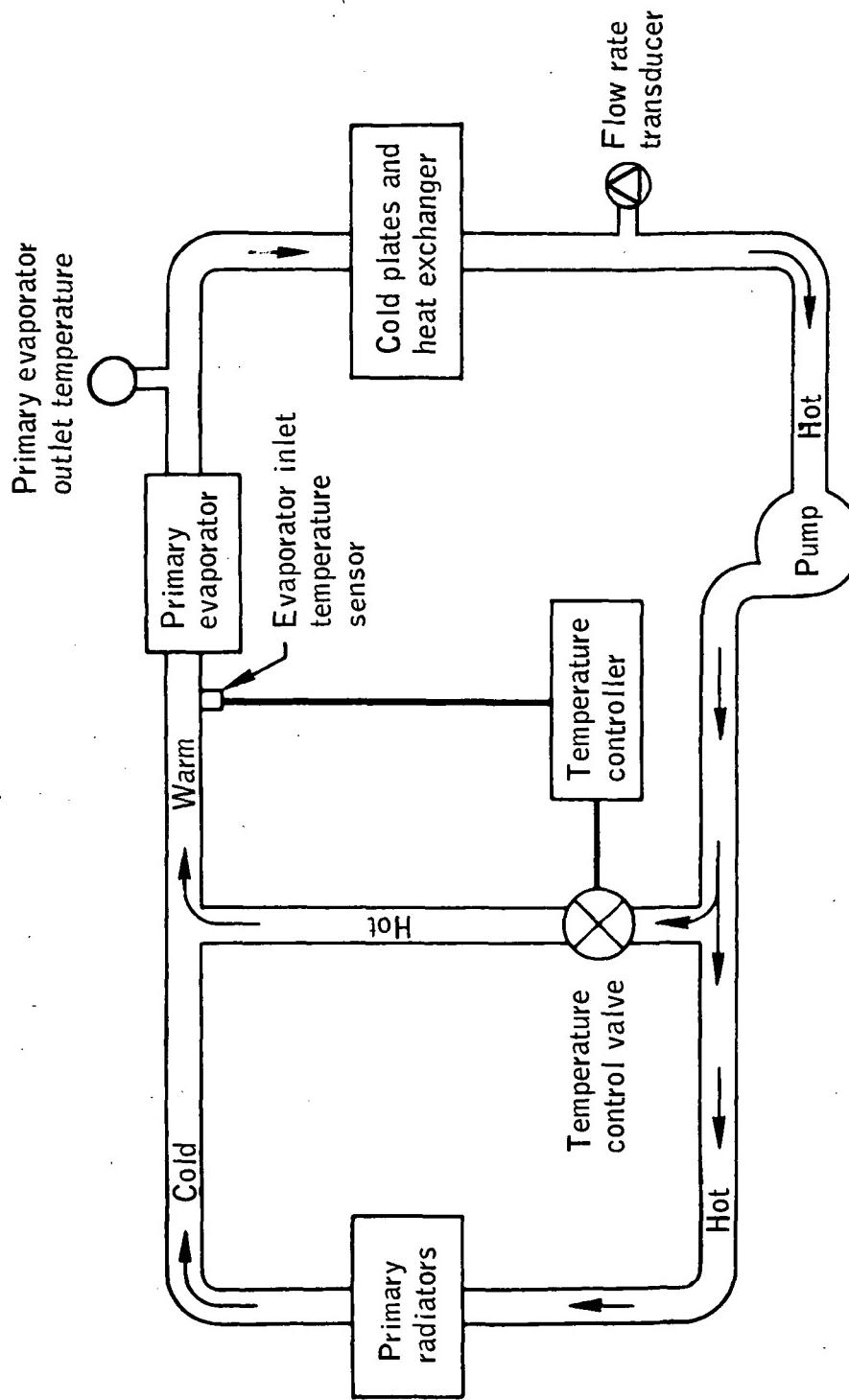


Figure 1.- Primary water/glycol coolant loop.

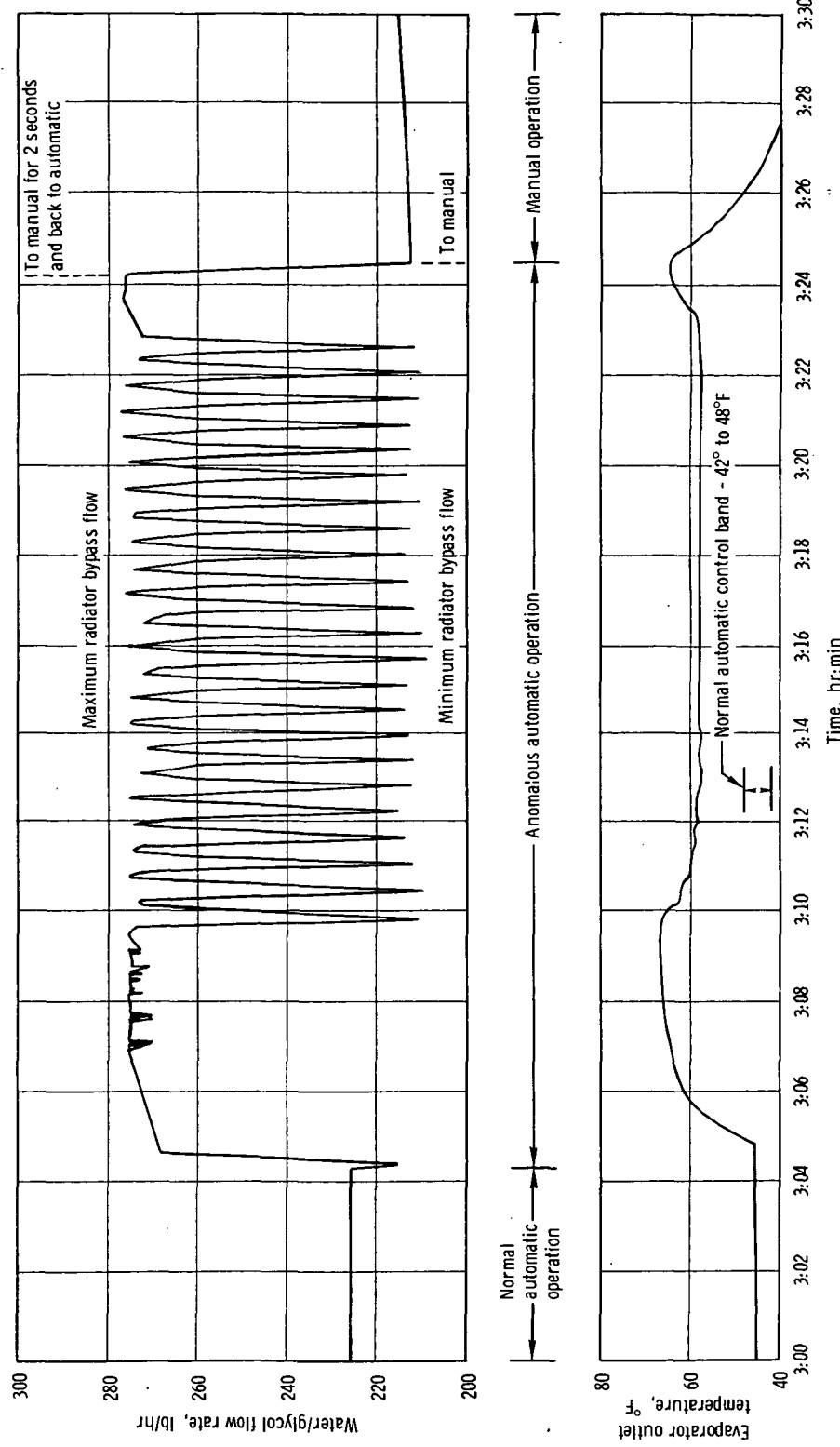


Figure 2. - Evaporator outlet temperature and system flow rate during anomalous period.

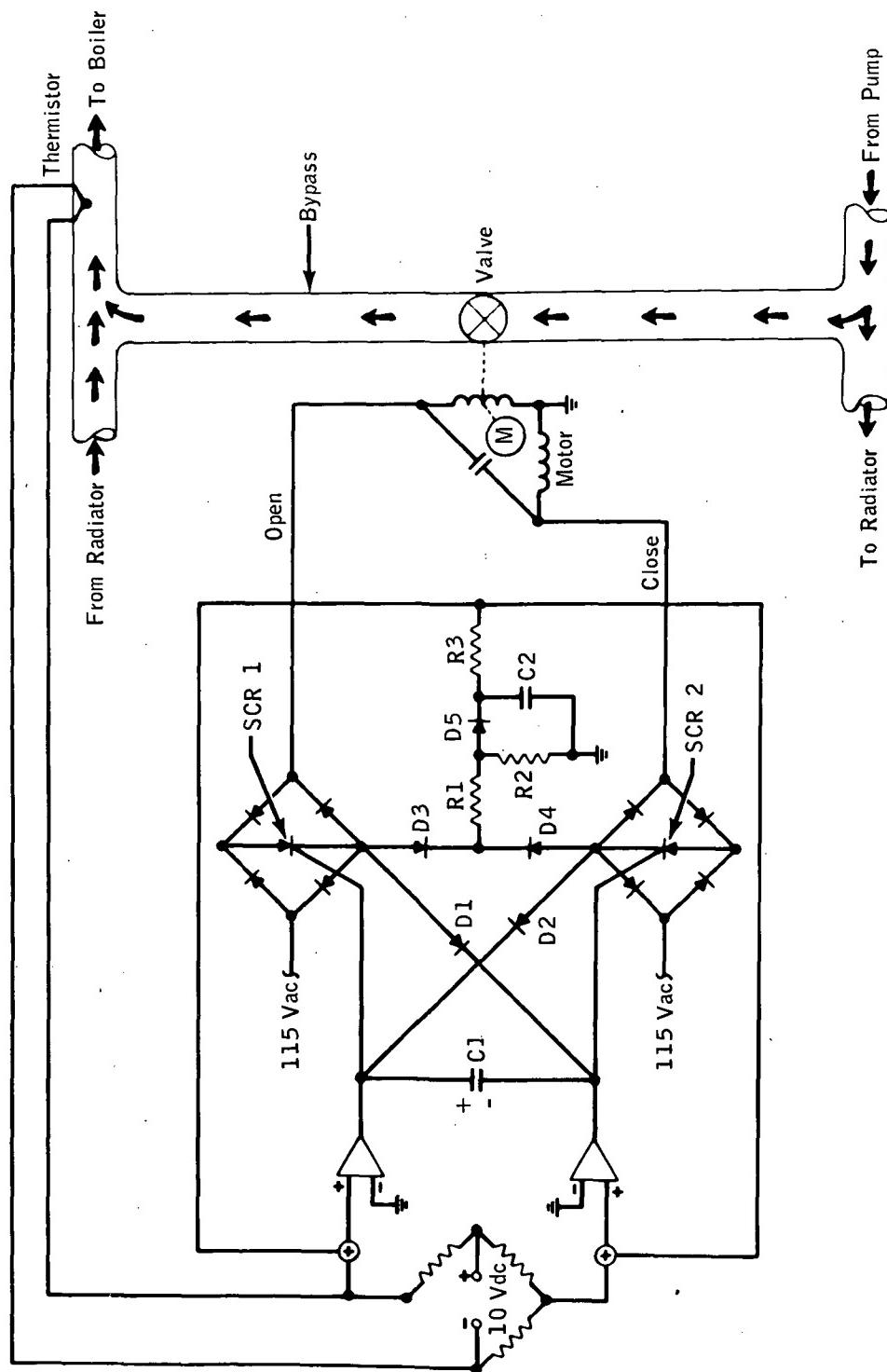


Figure 3.- Water/glycol valve controller.

and unbalances the bridge, supplying a positive voltage to the upper amplifier with respect to the lower amplifier. The output of the upper amplifier will, therefore, be driven more positive and the output of the lower amplifier more negative.

The difference between the two amplifier output voltages appears across capacitor C1. The voltage across this capacitor is applied between the gates and cathodes of the output silicon-controlled rectifiers SCR 1 and SCR 2 through the steering diodes D1 and D2. When the plus side of the capacitor (fig. 3) becomes sufficiently positive to turn on the upper silicon-controlled rectifier (sensed temperature less than 42° F), 115 volts ac is fed through the upper output bridge to the motor, driving the valve open. Full-wave rectified 115 volts ac is also coupled through diode D3 to resistors R1 and R2, diode D5, and capacitor C2, resulting in charging capacitor C2.

The voltage across capacitor C2 is coupled back through resistor R3 to the inputs of both amplifiers. Capacitor C2 will charge until both amplifiers are saturated. When both amplifiers reach saturation, their output voltages are equal and no voltage appears across capacitor C1. The first silicon-controlled rectifier will then turn off and stay off until capacitor C2 discharges sufficiently through resistor R3 to allow the amplifiers to become unsaturated.

If the sensed temperature is still below 42° F, the cycle will recur until the valve is opened sufficiently to increase the sensed temperature to above 42° F. For sensed temperatures above 48° F, the second silicon-controlled rectifier is operated in a similar manner.

DISCUSSION

Tests isolated the problem to the temperature controller where three separate discrepant conditions existed. The first was that when one channel was intermittently hard on, the feedback voltage from capacitor C2 was zero instead of the normal 50 to 54 volts dc. The second and third conditions were that the two output silicon-controlled rectifiers each stayed on when the respective rectifier gate was opened.

The components associated with the feedback circuit (diodes D3, D4, and D5, resistors R1, R2, and R3, and capacitor C2 in fig. 3) were removed, tested electrically, and dissected. The room-temperature leakage of the solid tantalum capacitor was 25 microamperes, which is about eight times the normal value. When a capacitor of this type shorts in a current-limited circuit, the capacitor can reform or "heal" itself. It will thereafter exhibit higher-than-normal leakage current.

Resistors R1 and R2 (fig. 3) are located next to the capacitor C2 in the controller assembly. Since these resistors dissipate approximately 0.7 watt when either output channel is on, the capacitor can be heated to a temperature where the rated voltage decreases below the applied voltage, causing the capacitor to short. In a test, the capacitor temperature reached 200° F and the capacitor momentarily shorted and healed itself. The effect on the capacitor was higher-than-normal leakage.

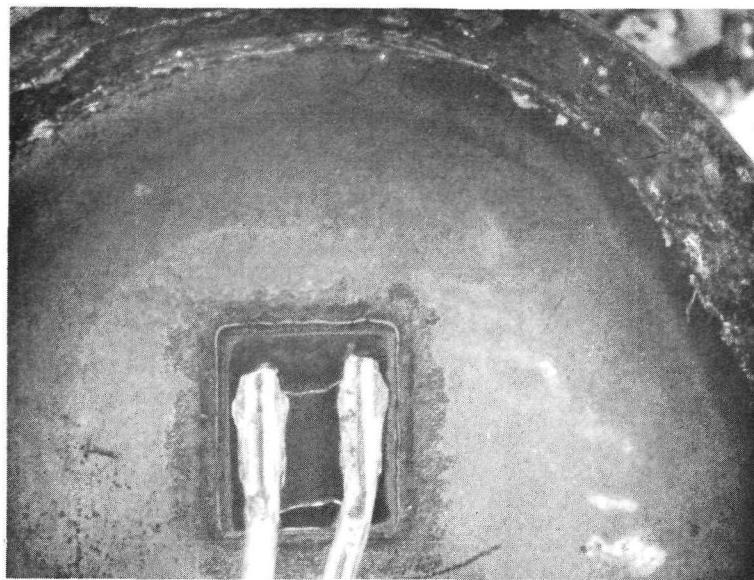
Analyses of flight conditions show that in a properly operating controller, the resistor heat dissipation would raise the capacitor temperature only about 112° F, which is not high enough to cause a short. Also, a shorted capacitor would not cause the controller to hold the valve full open for 5 minutes, as occurred in flight. The capacitor short, therefore, must have been a secondary failure, caused by an output silicon-controlled rectifier malfunctioning and staying on. Eventually, resistor heat dissipation raised the capacitor temperature high enough to cause a short.

Both output silicon-controlled rectifiers were removed from the controller for analyses. One rectifier semiconductor chip was found cracked (fig. 4). The other rectifier was pierced with a gas sampler and air was found inside the case instead of the required inert atmosphere. Oxygen inside the case can cause rectifier degradation. Both rectifiers were leak-checked and leak rates were about 100 times the specification value of 10^{-10} scc/sec. This value is high enough to allow atmosphere exchange during seven years since the device was manufactured.

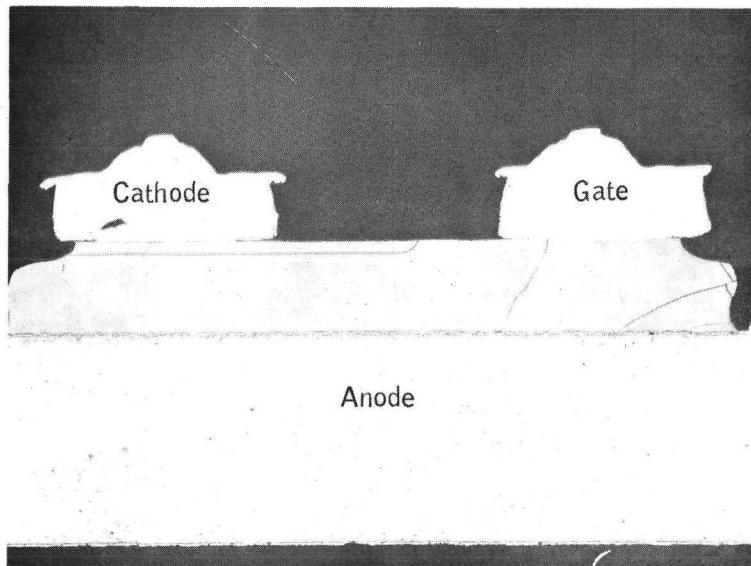
A controller on the Apollo 17 command module also displayed a continuous on condition in one channel. The rectifier in that channel also had a cracked semiconductor chip. The cracks in both the Apollo 16 and 17 rectifiers extended from under the gate lead, through both junctions, to the anode as shown in figure 4.

The cracks in the semiconductors could have been caused in manufacturing, during thermal-compression bonding of the large aluminum gate lead to the chip, or by handling when the controller was being assembled. Many failures occurred because of handling after the units used in the water/glycol temperature controllers had been manufactured. As a result, the manufacturer changed the design of the rectifier case because flexing of the base by forming the leads was cracking the chips.

Experience has shown that surface contaminants in a crack extending from the anode to the gate can provide a leakage path between the rectifier anode and gate (ref. 1). Further, resistance of such a leakage path will decrease as the temperature and applied voltage increase, and will decrease with time when a constant voltage is applied.



(a) Semiconductor chip mounted in header.



(b) Cross-section of chip showing cracks.

Figure 4.- Defective silicon-controlled rectifier.

Current flowing through the leakage path from the anode to the gate can turn the device on. Since the required gate current and the leakage path resistance will both decrease as the temperature increases, self-gating will occur at high operating temperatures.

Tests have shown that the defective silicon-controlled rectifiers which malfunctioned in the Apollo 16 and 17 controllers can be detected by measuring forward breakdown voltage at ambient and elevated temperatures. A device which fails this test is unusable. On the other hand, a device which passes this test is not necessarily good.

CONCLUSIONS

The output silicon-controlled rectifier semiconductor chips were cracked. Surface contamination in the crack then allowed the device to self-gate on and remain on, resulting in a secondary failure of the feedback capacitor.

CORRECTIVE ACTION

All remaining controllers have been tested for forward breakdown voltage at ambient and elevated temperatures. This test is the only practical test that can be performed and the test is not totally conclusive. If a controller fails in flight, manual valve control is satisfactory.

REFERENCE

1. Fedetov, Ya. A.: Principles of the Physics of Semiconductor Devices.
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